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Abstract:

A country’s existing emission standard policy will lead to a “lock in” effect. When the country plans to adopt new market-based instruments to control greenhouse gas emissions, it must consider this effect as it chooses among instruments to avoid larger efficiency loss. In this paper, we find that the “lock in” effect will cause a kink point to occur on the marginal abatement cost (MAC) curve. This change of shape for the MAC curve reminds us to be cautious in choosing market-based instruments when applying Weitzman’s rule. We also introduce this concept into a dynamic multi-regional computable general equilibrium (CGE) model for China and simulate MAC curves for all regions. After applying Weitzman’s rule, we propose a timeline for introducing price instruments under different marginal benefit (MB) curve scenarios.

Keywords:

Lock-in Effect, Marginal Abatement Cost Curve, Cap and Trade of Carbon Emissions Rights, Carbon Tax

I. Introduction

To tackle climate change and environmental degradation, China has already implemented a few mandatory policies to disentangle its economic growth from the rapid expansion of greenhouse gas emissions. Intensity regulation has been implemented in the 12th Five-Year Plan (2011-2015) to reduce energy-related CO_2 emissions per unit of economic output by 17% from 2010 levels. Another intensity target is the Copenhagen commitment by which carbon intensity would be reduced by “40%-45%” in 2020 from the level in 2005. One great step beyond the existing intensity targets is the latest official announcement from China stating its intent to peak its overall GHG emission before 2030. As a fast-growing emerging economy, China has realized the need to optimize social abatement costs by introducing more market-based policy instruments beyond traditional command-control policies. However, in this paper we show that the existing intensity standard will cause a policy “lock in” effect, which will make it difficult to choose among market-based instruments.

The "lock in" effect results when firms in one region adopt particular clean technologies to achieve the existing intensity standard. This "lock in" effect distorts firms' optimal behaviour and leads to a change in the shape of the marginal abatement cost (MAC) curve. In this paper, we show that a kink point will occur on the MAC curve. According to Weitzman (1974), the relative slopes of the MAC curve and the marginal benefit (MB) curve are the main determinant in choosing between price and quantity instruments under uncertainty. Thus, the kink point of the MAC curve becomes a quite important factor in choosing appropriate instruments.

II. China's choice of market based instruments

Among market-based policy instruments, cap and trade and carbon tax are the two most prevalent. The former controls the quantity of total carbon emissions and the latter controls the price per unit. Given that both of these policies have pros and cons, addressing how to design an appropriate policy regime in contemporary China is urgent. There is little domestic experience to learn from, partly because of the imperfect environmental tax system and the lack of a mature emissions trading system. Moreover, there is no consensus from experiences in developed countries about cost-benefit or cost-effectiveness nor are there even well acknowledged efficiency impacts from the two policies. Therefore, price or quantity control is worth validating in China's low-carbon policy regimes.

Theoretically, emissions trading and a carbon tax are equal in a competitive market with symmetrical information, and they can both reach the Pareto optimal result. However, the theoretical prediction is violated by many uncertainties arising from market conditions. Weitzman (1974) states that the choice of quantity and price control measures is dependent on the relative slope of the marginal cost curve and the marginal benefit curve of emission reduction. Therefore， uncertainties with the supply and demand behaviour of emission-reduction activities should be considered when choosing whether to control price or quantity in pollution mitigation practices. In China's domestic context, the appropriate policy tool with the least loss of economic efficiency must take these uncertainty factors into consideration for at least three reasons. Firstly, because China is in a stage of economic structural transformation, the dynamics of industrial upgrading and relocation strengthen the uncertainties of emission-abatement activities. Secondly, regional disparities across China are prominent sources of uncertainty because the more than 30 provinces have distinct economic structures, resource endowments and market conditions. Any unified low carbon policy scheme at the national level would mean different abatement costs in each province. Last but not least, the existing command and control policy—i.e., an in-place mandatory emission intensity target in each region—has some policy induced “lock-in effects”[1] with regard to low-carbon technology implementation and innovation. Abatement cost paths drive the pattern of costs and benefits for abatement activities in the short and long run and would distort the process of choosing a policy. Because all of these factors influence emission-abatement activities in various ways, the characteristics of marginal abatement cost curves should be investigated carefully to develop more appropriate low-carbon policies in China.

As pointed out by Weizmann (1974, 1978), the comparative advantages of policy instruments are critically depend on slopes of marginal benefit curve and marginal cost curve.[2] That is, if the absolute value of the slope of the MB curve is less than the absolute value of the slope of the MAC curve, then price control policies (such as a carbon tax) will be more efficient than quantity control policies (such as cap and trade). Otherwise, the quantity control policies will be more efficient and the difference in efficiency will increase with the increase in the difference between the two slopes. Stranlund and Ben-Haim (2008) extended Weitzman’s model to the situation with unstructured uncertainty, finding that the rule proposed by Weitzman still holds. In addition, this rule has been used by many researchers in both simulation and empirical analysis (Pizer, 1999, 2002; Parry et al., 1999). Shinkuma and Sugeta (2016) extends the comparison of policies to long-term period and find Weitzman’s rule does not always hold when there exists entry costs of firms and asymmetric information. In their analytic general equilibrium model, when entry costs are low, magnitude of asymmetry information is large and the size of output market is large, then an ETS is superior to a tax scheme even when Weitzman’s condition for the superiority of taxes is

[1] In existing economic literature, “lock-in effect” is mostly referred to “technology lock-in effect” which is a form of economic path dependence whereby the market selects a technological standard. In context of this paper, “lock-in effect” is defined as a path dependence of emission abatement effort caused by mandatory emission intensity target policy, which is called policy induced “lock-in effect”.

[2] Theoretically, price instrument and quantity instrument are equal if there is no uncertainties. However, factors such as external shocks, asymmetric information and biased estimation will all bring uncertainties to get exact marginal benefit and marginal cost functions, Weitzman’s rule is particular instructive in practical.

met.

Currently, the academic consensus is that the shape of the MB curve is relatively flat. Kolstad (1996) finds that each year's greenhouse gas emissions contribute very little to global warming and that the negative effect of global warming is caused mainly by the total stock of greenhouse gas emissions. In this case, different climate policies will not change the MB curve greatly in a short period of time.

MAC curve is first applied to estimate cost for global warming abatement since 1991 (Jackson, 1991). And, henceforth, MAC curve has become a common tool to study global warming issues. However, derivation of MAC curve can be divided into two types, one is expert based curves or technology cost curves and another is model-derived curves. (Kesicki, 2011) Expert based MAC curve one can provide extensive technological details for reducing emissions. (McKinsey & Company, 2007) However, this kind of curve cannot represent feedbacks of macroeconomics. Model-derived MAC curve can be further devided into two group, one is derived from bottom-up models which contain detailed energy technologies (Vuuren et al., 2004; Chen, 2005; Kesicki, 2012) and another is derived from top-down models which allow macroeconomic feedbacks. (Dellink, 2004; Klepper and Peterson, 2006; Morris et al., 2012) The latter group of MAC curves is more suitable to assess total social welfare by taking all responses from producers and consumers as well as governments into consideration. (Klepper and Peterson, 2006)

McKitrick (1999) proposes a new class of MAC curve that may contain a kink point. He uses a partial equilibrium model to analyse a firm's optimal behaviour when there is an emission constraint. In his model, the firm has two ways to reduce emissions; one is to conduct abatement activities and the other is to reduce output directly. In the optimal solution, the firm will make a trade-off between the costs of the two methods and cause a kink point in the MAC curve. This result plays an important role in the selection of climate policies. Moreover, although McKitrick defines marginal abatement cost as marginal effect to profit by reducing last unit of emission in firm level, his model can be readily extended and applied to a general equilibrium framework to include more economy wide feedbacks.

In this paper, we extend McKitrick's model by introducing an emission intensity constraint. We find that an existing emission intensity constraint causes a "policy lock-in effect" and changes a firm's marginal output costs by an implicit output subsidy. We then introduce this mechanism into our CGE model to simulate dynamic MAC curves for all regions in China from 2007 to 2020. The article is organized as follows: Section 3 introduces the McKitrick model extension that will be integrated into the CGE model; Section 4 describes the framework of the dynamic multi-regional general equilibrium model; Section 5 gives the simulation results of regional dynamic MAC curves from 2007 to 2020; Section 6 conducts a robustness test of the CGE model considering uncertainties; Section 7 describes the conclusions and offers policy suggestions.

The main purpose of this paper is to add some numerical proofs for choosing between carbon tax and cap and trade systems in China. By examining the relationships between regional marginal abatement cost curves and emission reduction targets in the current Chinese policy context, this paper intends to shed some light on the ambiguous conditions for policy choice at the more disaggregated regional level.

III. An extended model of the kinked regional MAC Curve

In McKitrick's model, firms own profit-maximizing behaviour in a complete competitive market, and a new variable is added into the firms' cost functions to represent emission abatement activity. This micro-level analysis can also be applied to industry-level analysis if the conditions of the Klein-Nataf aggregation problem are satisfied. Klein (1946) stated that if the first-order conditions of individual firms are satisfied, then the aggregate production function must satisfy the same first-order conditions. Nataf (1948) showed that such an aggregate production function exists if and only if every firm's production function is additively separable in inputs. Therefore, as long as firms have production functions with this separability feature, we can apply the analysis to aggregate production at the industry level. For industrial sectors, each sector maximizes its profit:

$$\max \quad \pi_i\left(p_i, y_i, \mathbf{w}_i, a_i\right) = p_i y_i - c_i\left(\mathbf{w}_i, y_i, a_i\right) \tag{1}$$

$$\text{s.t } \bar{e}_i = e_i\left(y_i, a_i\right)$$

subscript i represents different regions involved in emission reduction. p_i is price for output, y_i is output level. $\mathbf{w}_i$ is a vector including input factors and their prices. a_i represents the abatement activities these regions take to reduce emissions, and it satisfies $a_i \geqslant 0$. So a_i can be any form which represents the above economic meaning. For example, if we define emission intensity as

$1/a_i$, then it means increase in abatement activity a_i will reduce emission intensity level. c_i is cost function of $\mathbf{w}_i$, y_i and a_i. e_i is emission function of y_i and a_i. We also assume that $c_y > 0$, $c_{yy} > 0$, $e_y > 0$, $e_{yy} \geqslant 0$, $e_a < 0$ and $e_{aa} < 0$[3].

The marginal abatement cost is then defined as the derivative of profit (π) with respect to the target emission level. In the optimal solution, we can obtain the marginal abatement cost when $c_a(w,y,0)>0$ at $a=0$ as:

$$\frac{\partial \pi_i}{\partial e_i} = \begin{cases} -c_{ia}\dfrac{\partial a_i}{\partial e_i} & 0 \le e_i < e_{i,kink} \\ \left(\dfrac{p_i - c_{iy}}{c_{ia}} - \dfrac{\partial a_i}{\partial y_i}\right)\dfrac{dy_i}{de_i} - c_{ia}\dfrac{\partial a_i}{\partial e_i} & e_{i,kink} \le e_i < e_i^* \end{cases} \tag{2}$$

$e_{i,kink}$ is the emission level when kink point occur and e^* is unregulated emission level. Here, abatement activity a_i can be either the investment in new equipment to reduce emissions or the costs related to developing new energy-saving technologies, such as human resources, materials and R&D costs. As shown in McKitrick's analysis, the property of the first derivative of the cost function with respect to abatement activity at point $a=0$ decides whether a kink point will occur on the MAC curve. When $c_a(w,y,0)>0$, the zero lower bound of abatement activity will not ensure that the first part in the bracket on the right side of second expression in equation (2) will always be zero, thus the shape of the MAC curve changes. At this time, formula of MAC curve turn into first expression in equation (2). When $c_a(w,y,0)=0$, the initial abatement activity is costless, and therefore the region is free to adjust the abatement activity when it faces a specific emission target. However, when $c_a(w,y,0)>0$, the initial abatement activity is quite costly; therefore the region can only increase this abatement activity when it faces a rather tight emission target. Consequently, the kink point of the MAC curve occurs.

To apply this framework in a large-scale simulation model, we must first set the form of emission constraint explicitly in equation (1). In reality, the most common policy linking abatement activity with emission is the emission intensity target at the regional level. The emission intensity is defined as one region's total emission level divided by its total output level. Here we define

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[3] These assumptions are almost the same as those in McKitrick's model. The only difference is that we assume the second derivative of e to y can also be zero, this won't change the results.

“emission intensity” as e/y and set $e(y,a)=y/a$, then this emission intensity is an endogenous variable solved by equilibrium conditions. Following above definitions, we can describe the relationship between emission, output, abatement activity and the intensity target as:

$$\frac{e_i}{y_i} = \frac{1}{a_i} \le Int_i \tag{3}$$

Int_i is region i's emission intensity target. We call this emission intensity as “emission intensity imposed by policy”, which is an exogenous parameter. Equation (3) is a traditional Kun-Tucker problem and we can see that one region’s abatement activity input is bounded by its emission intensity target Int_i. If one region sets a higher policy target that leads to a lower emission intensity, then the minimum abatement activity input level becomes higher.

When substituting equation (3) into (1) and applying the envelope theorem, we can clearly see the implicit output subsidy effect that lowers the marginal output cost[4], i.e., the cost of one method that can reduce emissions. This happens only if equation (3) is binding, which is described as the policy induced “lock-in” effect. When equation (3) is not binding, the emission intensity constraint will not affect a firm’s behaviour; thus there is no output subsidy effect.

The behaviour of abatement activity in equation (3) is consistent in the general equilibrium setting, which means that abatement activity increases as absolute emissions decrease. In CGE model, there are no exact abatement activities[5], so all abatement activity changes are realized through substitution effect and cost structure effect. To see this, we take the production function in CES form and the first order conditions, which give the conditional factor demand function as:

$$e_i^* = ef_i \cdot E_i^* = ef_i \cdot y_i \left[\sum_{j=1}^{n} \theta_j \left(\frac{p_j}{p_E} \right)^{1-\sigma} \right]^{\frac{\sigma}{1-\sigma}} \tag{4}$$

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[4] The envelope theorem indicates that marginal output cost is $C_y=c_y-\lambda Int$, which is lower than c_y if there is no emission intensity constraint. This method is also used in Holland (2012) to show the implicit output subsidy effect of emission intensity standards.

[5] CGE model is a top-down model using aggregate production technology assumption used in economic theory. This assumption is quite different from production technology assumptions used in most bottom-up models which may contain hundreds of detailed production technologies.

ef_i is the emission coefficient of energy input E_i in region i. θ_j is the cost share of input j, and p_j is the price of input j. σ is the elasticity of substitution of inputs.[6] Then the change in emission intensity is:

$$d\ln\frac{1}{a_i} = d\ln E_i - d\ln y_i = d\ln\left[\sum_{j=1}^{n}\theta_j\left(p_j/p_E\right)^{1-\sigma}\right]^{\sigma/1-\sigma} \tag{5}$$

Equation (5) shows that the change in intensity depends on the changes in relative prices, d(p_j/p_E) and the cost share of different inputs. This means that emission intensity will decrease as long as energy input is substitutable to other inputs. This effect will be magnified if the cost share of energy input increases.

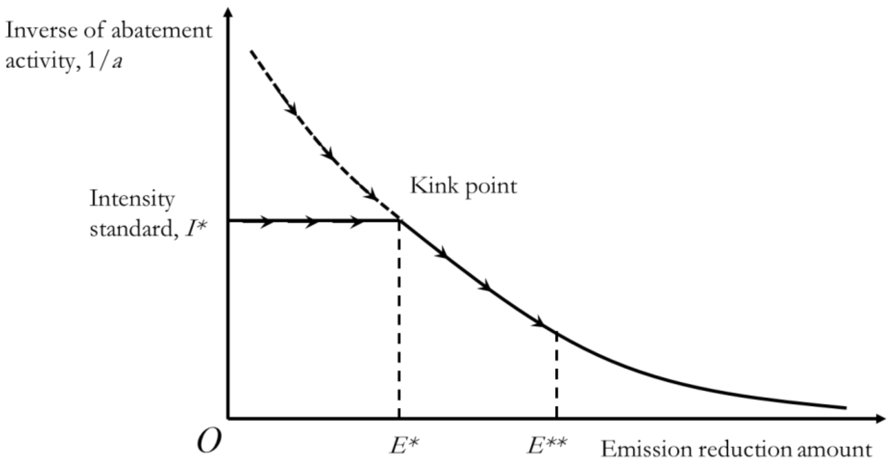

Figure 1 Mechanism of the occurrence of a kink point

Figure 1 illustrates the mechanism of the kink point concept in a large-scale simulation model. If one region has no intensity target, i.e., a pure null scenario, then the emission reduction efforts allow for unconstrained inputs of abatement activities, which correspond to a smooth dotted line in the figure. However, if one region initially had an emission intensity standard (e.g., I^*), then the abatement activity would be bounded at certain level greater than zero, as indicated in the solid line in this figure. This level of abatement activity corresponds to an inelastic effort other than the output change needed to achieve the intensity target. Once absolute emission E* was further reduced to a certain level such as E**, then the abatement activity would increase along with the solid line.

[6] We make a simplified assumption here that there is only one type of energy input.

From Figure 1, we can see that the position of the kink point depends on three elements. The first is the intensity target level: a lower intensity level will lead to a later occurrence of the kink point. The second element is the initial emission intensity level: if one region is originally energy intensive, then it will lead to a later occurrence of the kink point. The third element is the rate of decrease in true emission intensity level, which is related to abatement activity; this factor is affected by a region's relative price of inputs and cost share of inputs.

IV. The dynamic regional computable general equilibrium model

1. Model data

This paper builds a recursive dynamic multi-regional CGE model of China. The model uses *The 2007 Regional Input – Output Table* (National Bureau of Statistics of China, 2011) as the baseline to calibrate. It includes 30 regions (all provinces, cities and autonomous regions, except the Tibet and Hong Kong, Macao, and Taiwan regions). Each region includes 42 production sectors that correspond to the 42 sectors in the input-output table, one government and one representative household sector. Capital and labour are the only two endowment factors used in the model. The model is written in GAMS and uses MPSGE subsystems to obtain the entire equation system.

Rectangular Social Accounting Matrix (SAM)

A key problem with using an MPSGE subsystem is that we must first build a dataset called rectangular SAM (Rutherford, 1998), This dataset is just a different version transformed from conventional SAM table and it is also micro consistent that both row sums and column sums are zero.[7] We use a cross entropy method proposed by Robinson and El-Said (2000) to obtain the balanced rectangular SAM table based on *The 2007 Regional Input – Output Table*.

Inter-regional trade matrix

Another important problem in building a regional CGE model is building an inter-regional trade matrix dataset. First, we use the gravity model to estimate the raw interregional trade matrix based on regional inflow and outflow data. Then, the cross entropy method is used again to balance the extended rectangular SAM table, which includes the above raw interregional trade matrix. Finally,

[7] More detailed description of rectangular SAM table can be obtained from GAMS/MPSGE manual. (Rutherford, 1998)

we obtain a consistent dataset to build the regional CGE model.

Emission data

In this model, CO_2 emission in each period is calculated by multiplying inputs of five energy types[8] and adjusted emission factors. This process is constituted of two steps. First, emissions of different energy types in each region are calculated by the multiplication of final energy consumption data from energy balance table and default emission factor obtained from IPCC Carbon Inventory Accounting Guidelines. Next, we divide emission by energy inputs measured in monetary term in benchmark input-output table to get adjusted emission factors. These adjusted emission factors are assumed to keep constant during whole periods from 2007 to 2020.

2. Basic modules

The basic modules of the regional CGE model include a production module, a demand module, an energy/emission module and an interregional trade module.

Production

The production module employs nested constant elasticity of substitution (CES) production functions to specify substitution possibilities in production between capital, labour, energy and intermediate inputs. At the top level, intermediate inputs are used in fixed proportions, and they are aggregated with energy and a value-added composite of capital and labour.

According to equation (3), we introduce two new endogenous variables into the energy composite production procedure. One represents emission permits used in fixed proportions with different energy inputs. Revenues from these emission permits are cycled back to regional households. Another variable is the endogenous emission intensity, which is the inverse of abatement activity.

Final consumption demand

The utility function of the representative consumer in each region is given as a constant elasticity of transmission (CET) function, which consists of total consumption and net savings:

$$\max_{\{WLF,DINV\}} U_r = \eta \cdot \ln WLF_r + (1-\eta) \cdot \ln SAV_r \tag{6}$$

[8] Five energy types are coal, crude oil, natural gas, petroleum product and electricity.

WLF_r is region r's total residential consumption; SAV_r is region r's net saving; η is the share of consumption.

Total residential consumption, government consumption and investment demand within each region are all in the form of combined consumption of a CES energy aggregate and a CES non-energy consumption bundle.

Budget constraint

A household's total income comes from capital income, labour income, government transfer payments and revenue from emission permits. The government's total income comes from tax revenue.

Interregional trade

The interregional trade module assumes that each region follows small-country behaviour within an international trade market, which means that prices of import and export goods are all exogenous. While in the domestic market, each region follows big-country behaviour, meaning that each region is no longer a price taker but can affect the domestic price through its interregional trade volume.

For non-energy goods, a three-level nested CES demand function is used to specify substitution possibilities among goods from foreign countries, other domestic regions and the local market:

$$CONS_i = \left\{ \alpha_{i1} \left[\alpha_{i2} D_i^{-\varphi} + \alpha_{i3} \left(\left(\sum_r \theta_{ir} INF_{ir}^{-\delta} \right)^{-1/\delta} \right)^{-\varphi} \right]^{\rho/\varphi} + \alpha_{i4} IMP_i^{-\rho} \right\}^{-1/\rho} \tag{7}$$

$CONS_i$ represents the total consumption of non-energy good I; subscript r stands for the different regions. α and θ are share coefficients of different input goods. The Armington elasticity of substitution among goods from different sources is represented by φ, ρ and δ. *INF* and *IMP* stand for the interregional flow of goods and import goods, respectively.

We assume that energy goods from different countries and regions are homogeneous due to the high degree of standardization; therefore, the energy demand function is a standard CES function:

$$CONS_e = \left(\alpha_{e1} DS_e^{-\varepsilon} + \sum_r \theta_{er} INF_{er}^{-\varepsilon} + \alpha_{e4} IMP_e^{-\varepsilon} \right)^{-1/\varepsilon} \tag{8}$$

ε is elasticity of substitution among different sources.

3. Interregional capital flow module

In this model, we use the putty-clay capital assumption to differentiate capital. This means that once free capital is used to form durable goods, it cannot be converted back again. Thus, only newly formed capital in each period has the ability to flow across sectors and regions. Therefore, the adjustment of industrial structures and the relocation of industries can only be completed gradually by the depreciation of capital stock and the flow of newly formed free capital. Each region's total investment is determined by the total savings in the last period, which is the neoclassic macro-closure condition. Finally, the flow patterns of newly formed capital are determined by the difference among each region's rate of return of capital. In this model, we use the logit function proposed by Dixon (2012) in the MONASH Model to describe the relationship between the rate of return and the growth rate of capital stock:

$$g_{r,i}^{k} = \frac{\underline{\underline{g}}_{r,i}^{k} + \overline{\overline{g}}_{r,i}^{k} \cdot e^{cgk\left(RIE_{r,i}-\overline{RI}\right)} \cdot \left(\overline{g}_{i}^{k} - \underline{\underline{g}}_{i}^{k}\right) \Big/ \left(\overline{\overline{g}}_{i}^{k} - \overline{g}_{i}^{k}\right)}{1+e^{cgk\left(RIE_{r,i}-\overline{RI}\right)} \cdot \left(\overline{g}_{i}^{k} - \underline{\underline{g}}_{i}^{k}\right) \Big/ \left(\overline{\overline{g}}_{i}^{k} - \overline{g}_{i}^{k}\right)} \tag{9}$$

$g_{r,i}^{k}$ is the expected growth rate of the capital stock of sector *i* in region *r*. $\overline{\overline{g}}_{i}^{k}$, $\underline{\underline{g}}_{i}^{k}$ and $\overline{g}_{i}^{k}$ stand for the upper bound, lower bound and equilibrium level of the capital growth rate of each sector, and we take the value as 0.3, 0 and 0.16, respectively. *RI* stands for the equilibrium value of the rate of return on capital, which is calculated from the *2007 Input - Output Table*. Figure 2 depicts the relationship between the expected return on capital (RI^{e}) and the growth rate of capital accumulation ($g_{r,i}^{k}$) with the form of logit function.

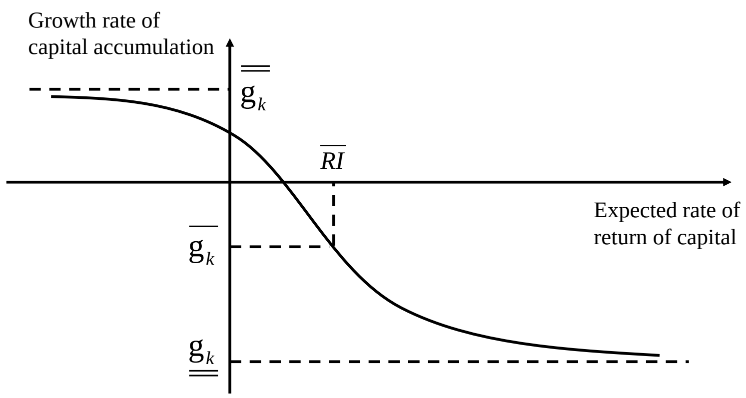

Figure 2 Relationship between capital accumulation and expected rate of return

4. Interregional labour flow module

Another important characteristic of this model is that labour can flow among regions, and the degree of interregional labour flow is determined by each region's total labour supply in the previous period, wage differences among regions and other exogenous parameters. Because value-added data for rural labour and urban labour are not separated in China's input-output table, this model assumes that there is only one type of labour.

The pattern of labour flow is captured by the extended Lewis model, which takes incomplete labour flow into consideration. Thus, the labour transfer equation is set as:

$$LM_{d,r}^{t} = \Theta_{d,r} \cdot \phi_{d,r}^{t} \cdot \left[\frac{\left(\mu_{d,r} - m_{d,r}\right) W_r^{t-1}}{W_d^{t-1}} \right]^{\sigma} \cdot L_d^{t-1} \tag{10}$$

t represents the year; subscript d and subscript r stand for the local and the targeted region, respectively. $LM^{t}_{d,r}$ stands for the amount of labour transferred from the local region to region r in period t, and it is in proportion to the total labour force L^{t-1}_{d} of the local region in period t-1. W_d and W_r represent the real wage in two regions. $\mu_{d,r}$ stands for the differences in the labour quality of two regions; we set $\mu_{d,r}$ equal to one in this model. $m_{d,r}$ represents the cost of labour migration in the form of a certain percentage of the wage level in the targeted region; we assume $m_{d,r}$ equals 0.05. Finally, σ stands for the elasticity of labour transfer to capture the incomplete labour flow situation, and we assume σ equals 0.8. (Xu and Li, 2008)

In equation (10), $\Theta_{d,r}$ represents the transfer intensity coefficient of the labour flow from this region to the targeted province. It is a constant; therefore, it does not change over time. The coefficient is calculated by the data from *Tabulation on the 2010 Population Census of the People's Republic of China* (2012). $\Phi^{t}_{d,r}$ is a dummy variable that represents the existence of positive labour flow. When labour flow exists, the variable takes the value one, but it otherwise takes the value zero.

5. Scenario settings

During the years 2005 to 2010, all provinces in China made great achievements in energy savings and emission reductions as required by the Eleventh Five-Year Plan. Moreover, the Twelfth Five-Year Plan announced further plans to reduce energy consumption per unit of GDP by 18% and carbon emissions per unit of GDP by 17%. To implement these targets, the State Council released the *Work Plan for Controlling Greenhouse Gas Emissions for the Twelfth Five-Year Plan Period* and proposed clear emission reduction targets for all regions for the years 2010 to 2015. China committed at the Copenhagen Conference to further promote energy savings and emission reductions by 2020 and to cut CO_2 emissions per unit of GDP by 40% as compared with 2005. Following these climate policies, we establish the business-as-usual (BAU) scenario of emission intensity targets for all regions in China from 2007 to 2020.

In this type of BAU scenario, one should be cautious in calculating the marginal abatement cost. In a traditional dynamic recursive model, the dynamic behaviour of endowments and parameters follow several rules that are determined exogenously under a NULL scenario. Compared to the BAU scenario, the NULL scenario imposes no climate policy restrictions; it is clearly unsuitable to discuss effects without accounting for existing abatement efforts from previous years. Therefore, one advantage of considering existing policies is that we can explore the actual cost of policies that reflect dynamic changes in the economy.

To realize this BAU scenario setting, we first define two emission intensity variables; one is the endogenous intensity Int^{t}_{base} and another is the exogenous policy target $\mathrm{Int}^{t-1}_{\mathrm{BAU}}$, and $\mathrm{Int}^{t}_{base}=\mathrm{Int}^{t-1}_{\mathrm{BAU}}$. This indicates that emission intensity in year t has an upper bound of the intensity target in year t-1.

For the CGE model, the entire model equation system can refer to the representation of Abdelkhalek and Dufour (1998):

$$\mathbf{Y} = f\left(\mathbf{X}, \boldsymbol{\beta}, \boldsymbol{\gamma}\right) \tag{11}$$

If there are n endogenous variables in the CGE model, then $\mathbf{Y}$ is an endogenous variable vector of $n \times 1$. $\mathbf{X}$ is an exogenous variable vector (e.g., policy variable). β is the free parameter vector, and $\boldsymbol{\gamma}$ is the calibrated share parameter vector. We can then calculate each region's total emissions in the BAU scenario in year t using:

$$\mathbf{e}^{*,t}_{base,t} = \mathbf{EF} \cdot f\left(\mathbf{X}, \boldsymbol{\beta}, \boldsymbol{\gamma} \mid \mathbf{Int}^{t}_{base} = \mathbf{Int}^{t-1}_{BAU}\right), \mathbf{Int}^{t-1}_{BAU} \subset \mathbf{X} \tag{12}$$

e^{*}_{base} is the $j \times 1$ vector of regional total emissions used in equation (1). **EF** is the $j \times n$ matrix of the emission coefficient of all regions. **Int** is the $j \times 1$ vector of emission intensity of all regions. Hence, we can obtain the marginal abatement costs for all regions under the constraint **target**:

$$\mathbf{MAC}_{\mathbf{e}}^{t} \Leftarrow f\left(\mathbf{X},\boldsymbol{\beta},\boldsymbol{\gamma} \mid \mathbf{e} \le \left(\mathbf{I}-\mathbf{target}\right)\mathbf{e}_{base}^{*,t}, \mathbf{Int}_{base}^{t} \le \mathbf{Int}_{BAU}^{t}\right) \tag{13}$$

Here, **target** is a $j \times j$ diagonal matrix that represents each region's target emission reduction rate. This reduction rate is set exogenously from 0 to 50% in 1% increments to simulate the MAC curve. Figure 3 illustrates the dynamic MAC curves in the BAU scenario.

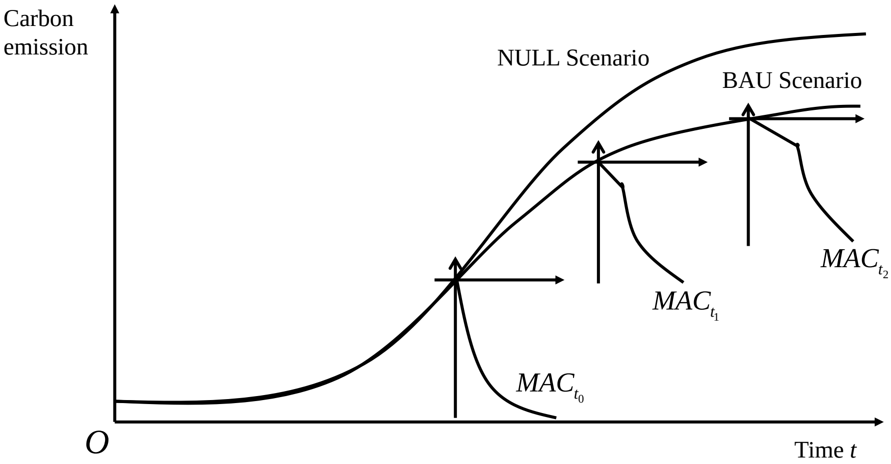

Figure 3 The dynamic MAC curve based on the BAU Scenario

V. Simulation results and analyses

1. Shapes of regional MAC curves

Figure 4 presents the MAC curve results of two regions, Beijing and Qinghai. The figure shows the surface of marginal abatement costs combining two dimensions. One dimension is the years from 2007 to 2020 and the other dimension is an emission reduction rate from 0 to 50%. The MAC surfaces of all other regions look similar, with the only difference being their absolute level. This confirms our basic economic intuition that if one region stays at the current emission intensity level, then it will have no extra abatement cost, and if the emission reduction target becomes tighter, the result will be higher abatement costs.

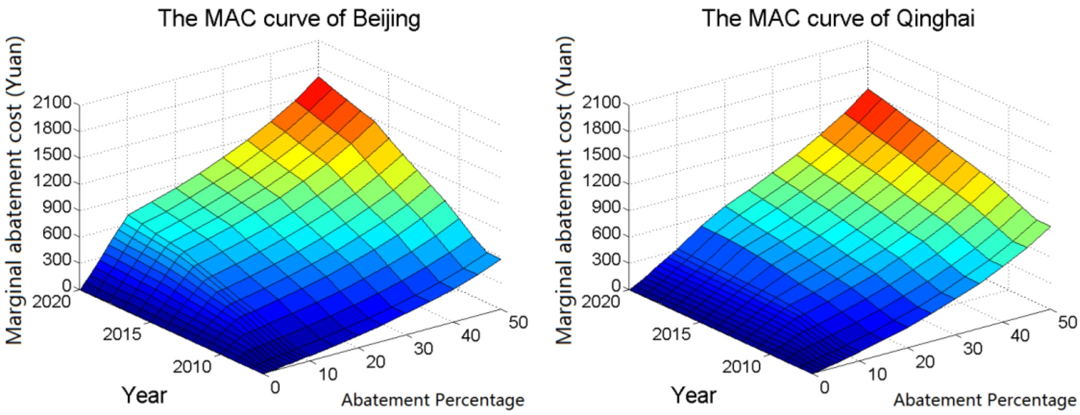

Figure 4 The surface charts of the dynamic MAC curves of Beijing and Qinghai

The MAC curve of Beijing can be seen as a representative curve because most regions' curves have a similar shape. However, only Qinghai's MAC curve appears to be quite flat. We can see this result more clearly in Figure 5 if we depict each year's MAC curve individually. The results confirm the theoretical prediction about the shape of the MAC curve: kink points will occur as the target becomes tighter, regardless of the slope of the MAC curves.

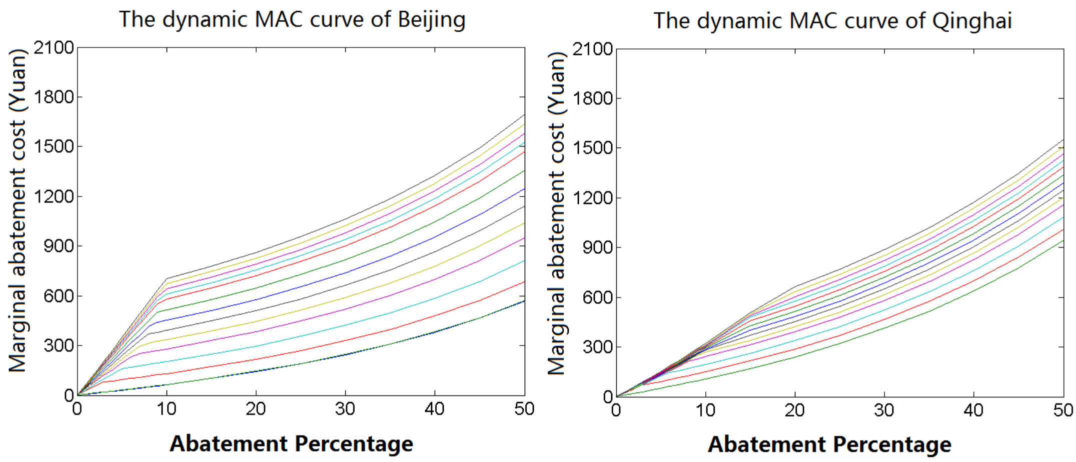

Figure 5 Cross-sectional views of the dynamic MAC curves of Beijing and Qinghai

Note: From bottom to top is the MAC curve under different abatement rates each year from 2007 to 2020.

From the results shown in Figure 5, we can draw two preliminary conclusions about regional dynamic MAC curves.

Firstly, the absolute level of the MAC curve increases over time. If one region faces the same reduction target every year, the abatement cost will go up gradually, which corresponds to common sense. In the BAU scenario, it becomes increasingly difficult to reduce the same percentage of emissions because the emission intensity constraint changes monotonically, causing the MAC curve to shift upward.

Secondly, kink points occur and shift to the right over time. As shown in the theoretical model, there are two ways to reduce emissions: reducing output directly and increasing abatement activities. Each region will make a trade-off between the costs of the two choices. On the one hand, when the cost of reducing output exceeds the abatement activity cost, both methods will be adopted and thus lead to kink points. On the other hand, when the intensity target becomes stricter, it becomes more difficult to reduce emissions. This trend leads to an increase in the initial abatement activity cost, which has the potential to reduce output. As a result, the occurrence of kink points is delayed.

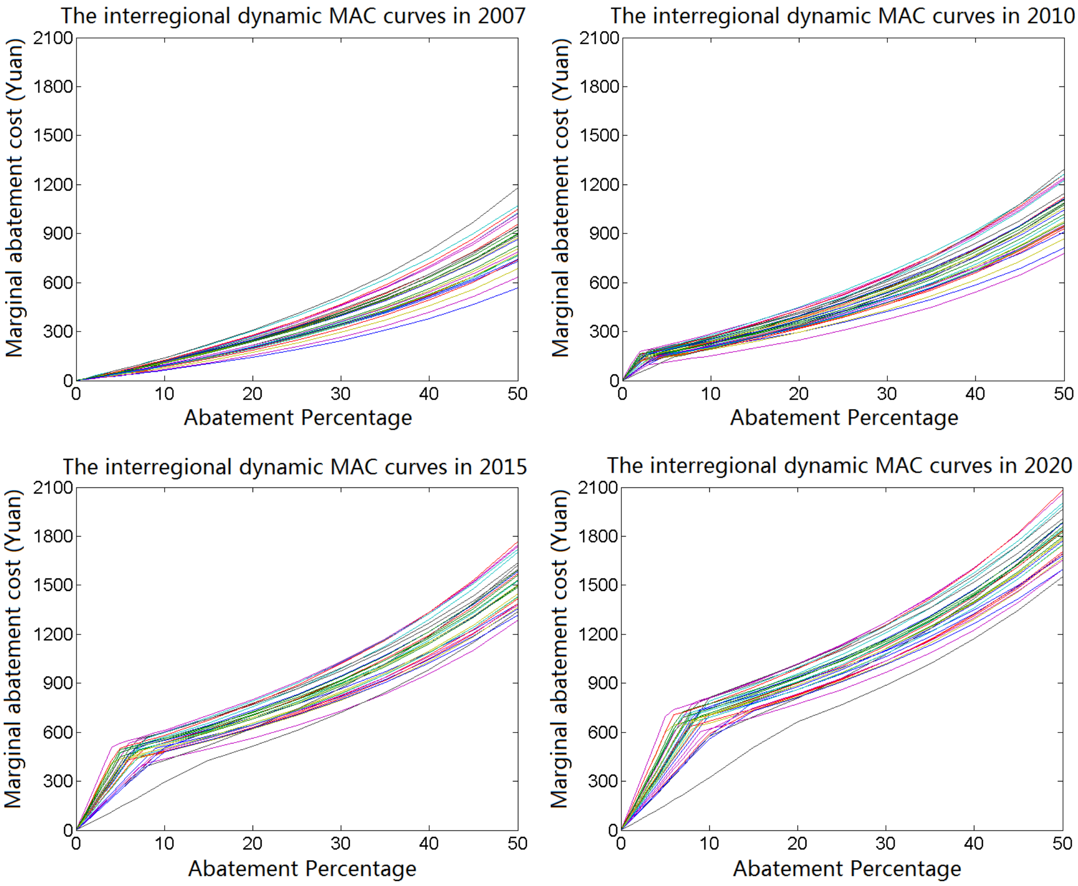

Figure 6 The comparison between different regions' dynamic MAC curves

Note: Each kinked line represents one region's MAC curve.

Figure 6 shows the comparison of MAC curves among all regions for four different years. As mentioned previously, only the MAC curve of Qinghai Province has a quite different shape than those of other regions. According to equation (5), this is because Qinghai Province has a relatively low cost share of energy input, so the increase rate of abatement activity is also relatively low. This makes its MAC curve very similar to the traditional one. However, the results in Figure 6 show that kink points occur after 2007 and that they change the shape of the MAC curves substantially in the years 2015 and 2020. Most kink points occur when emission reduction rates range from 4 to 10% in 2015 and between 5 to 15% in 2020. Most of these differences result from the mixed effects of the cost share of energy inputs and changes in relative prices according to equation (5). Different emission intensity settings in the BAU scenario also account for some of the differences.

2. Making policy choices between taxes and a cap and trade system

To support the policy choices between a tax and a cap and trade system, we need to know the relative importance of various factors driving the appearance of the kinked points. Based on equations (3) to (5), which indicate the mechanisms of the kink point, we can write the emission reduction rate corresponding to the kink point as a function of three types of elements: initial emission intensity, intensity target and energy input cost shares:

$$\begin{aligned} percent_{kink} &= f\left(Int, IntT, \mathbf{Share}\right) \\ \mathbf{Share} &= \left(Sh_{coal}, Sh_{oil}, Sh_{oilproduct}, Sh_{ele}, Sh_{heat}\right) \end{aligned} \tag{14}$$

in which $percent_{kink}$ is the emission reduction rate corresponding to the kink point, *Int* is the initial emission intensity, and *IntT* is the intensity target. **Share** is a vector of different energy input cost shares, which include the cost share of coal, oil, oil products, electricity and heat. We then apply the Taylor expansion to equation (14) to obtain the regression equation:

$$\begin{aligned} percent_{kink,it} = {} & \alpha_0 + \alpha_1 Int_{it} + \alpha_2 IntT_{it} \\ & + \alpha_3 Sh_{coal,it} + \alpha_4 Sh_{oil,\mathrm{it}} + \alpha_5 Sh_{oilprod,it} + \alpha_6 Sh_{ele,it} + \alpha_7 Sh_{heat,it} + \varepsilon_{it} \end{aligned} \tag{15}$$

Equation (15) is a panel data model, and we obtain all data needed from the simulation result of the CGE model. A Hausman test ruled out the null hypothesis, and thus we established the model as a fixed-effect model. Moreover, we estimated the model using the cross-section weighted least squares method. This was motivated by our intuition that regions are differentiated by many aspects, such as production technologies and household preferences. A White test also suggested that the model shows heteroscedasticity. The regression results are shown in Table 1.

Table 1 Regression results of panel data

	Coefficient
C	0.089***
	(0.034)
Int	0.112**
	(0.056)
$IntT$	-0.283***
	(0.012)
Sh_{coal}	-3.632***
	(0.374)
Sh_{oil}	6.969***
	(1.078)
$Sh_{oilprod}$	0.405***
	(0.130)
Sh_{ele}	0.350**
	(0.137)
Sh_{heat}	8.940***
	(2.113)

*** and ** indicate that the coefficient is significant at the 1% and 5% levels, respectively.

Not surprisingly, the results in Table 1 indicate that a higher initial intensity target will lead to later occurring kink points and that a higher intensity policy target will delay the occurrence of a kink point. This is consistent with the theoretical prediction shown in Figure 1.

Estimation results show that shares of different energy inputs contribute quite differently to the occurrence of a kink point. The negative coefficient of Sh_{coal} indicates that an increase in the cost share of coal will cause the intensity curve in Figure 1 to become steeper. This change results from the larger substitution effect of the coal input. Consequently, this effect moves the intersect point leftward, which accelerates the occurrence of a kink point. However, the estimation results show that all other energy inputs are opposite to coal and that an increase in cost shares of these energy inputs will delay the occurrence of a kink point.

VI. Policy choice analysis

According to Weitzman's rule, when the MAC curve appears to be relatively flat, it will be more efficient to adopt quantitative policies such as emission trading, whereas it will be more effective to adopt price policies such as a carbon tax when the MAC curve appears to be relatively steep.

Following the simulation results in this paper, the occurrence of kink points divide the MAC curve into two parts—one flat and the other steep. Therefore, it is essential to take this result into consideration when implementing emission reduction policies.

To apply Weitzman's rule, we need to further identify the slope of the MB curve. There is a consensus that the marginal damage from greenhouse gases is constant, which means a quite flat MB curve. However, when facing environmental problems, people are more likely to pay attention to regional air pollution; this is especially true in China. As a result, when estimating the MB curve, the ancillary benefits of greenhouse gas reduction should also be taken into consideration. There are already many studies of the ancillary benefits of addressing two environmental problems. Some of these studies use an integrated environmental assessment model or sector-specific analysis to investigate the co-benefit of climate change policy and regional air pollution control policy. (Syri et al., 2001; Alcamo et al., 2002; Mayerhofer et al., 2002; van Vuuren et al., 2006; Takeshita, 2012) More recently, a few researchers have begun to study these co-benefits in China. Zhang et al. (2015) combine the energy conservation supply curves and the GAINS model to study the co-benefit in China's cement industry. They find that energy efficiency measures and end-of-pipe options in China can achieve emission reductions at a relatively low cost. Dong et al. (2015) combine the AIM/CGE model with the GAINS model to assess co-benefits at China's provincial level. They find that co-benefits exist at the provincial level and that regions with higher GDP will obtain higher cost-reduction co-benefits. All of these studies show that when the ancillary benefits of greenhouse gas reduction are considered, the new MB curve may not be as flat.

Due to these uncertainties in estimating the MB curve, we set a wide range for the slope of the MB curve and compare the slopes of the MB and MAC curves. The comparison shows the conditions under which price policies dominate or at least are better than quantity policies.

Table 2 Policy selection matrix between price policies and quantity policies

	Slope of MB curve, 10,000 yuan/percent										
Year	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
2007	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2008	100%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2009	100%	37%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2010	100%	57%	7%	3%	3%	0%	0%	0%	0%	0%	0%

2011	100%	63%	10%	7%	7%	3%	3%	0%	0%	0%	0%
2012	100%	77%	7%	3%	3%	0%	0%	0%	0%	0%	0%
2013	100%	80%	33%	30%	30%	27%	27%	7%	3%	0%	0%
2014	100%	97%	60%	53%	53%	50%	50%	33%	17%	10%	3%
2015	100%	97%	83%	80%	80%	73%	67%	57%	27%	17%	7%
2016	100%	100%	100%	97%	97%	97%	77%	63%	40%	27%	13%
2017	100%	100%	100%	100%	97%	97%	80%	67%	43%	27%	13%
2018	100%	100%	100%	100%	97%	97%	80%	73%	43%	27%	17%
2019	100%	100%	100%	100%	97%	97%	80%	73%	50%	27%	20%
2020	100%	100%	100%	100%	97%	97%	83%	73%	60%	33%	20%

The number in each cell of Table 2 is the percentage of regions that should enact price polices, according to Weitzman's rule. The light area in Table 2 means that few regions should adopt price instruments, whereas the dark area means that most regions should adopt price instruments. When we consider the ancillary benefits of greenhouse gas reduction, the slope of the MB curve may become even steeper. This means that it is more likely that the real world will be located in the light area in Table 2. In this case, quantity instruments are definitely better than price instruments.

Next, we assume that the slope of the MB curve is 3,000 yuan/percent. According to Weitzman's rule, we then summarize the policy choices of each region in Table 3.

Table 3 Summary of regions that should switch from a quantity policy to a price policy

Year	Regions
2010	Hainan
2011	Henan
2013	Hebei, Jilin, Heilongjiang, Shanghai, Anhui, Jiangxi, Hunan, Chongqing
2014	Shanxi, Hubei, Guangxi, Sichuan, Guizhou, Gansu, Xinjiang
2015	Inner Mongolia, Liaoning, Jiangsu, Zhejiang, Shandong, Yunnan, Ningxia
2016	Beijing, Tianjin, Fujian, Guangdong, Shaanxi
2017	Qinghai

The results in Table 3 show that most regions entered the "steep slope" part of the MAC curve between 2013 and 2014, which causes the slope of the MAC curve to become greater than that of the MB curve. Therefore, assuming that the slope of the MB curve is 3,000 yuan/percent, the simulation results suggest imposing carbon taxes rather than implementing an emission permit-trading scheme in all regions from 2016 to avoid extra economic efficiency loss under uncertainty.

VII. Concluding remarks

In this paper, we find kink points will occur in MAC curves due to policy induced “lock-in effect" caused by introduction of emission intensity target policy. When imposing intensity target policy, "lock-in effect" restricts agents to reduce emissions only through reducing output level, that is to say, agents' ability to choose emission abatement effort level is locked in by emission intensity constraint. Under this circumstance, the choice of market based carbon policy under uncertainty should be decided more seriously.

After introducing fore-mentioned kink point mechanism into a dynamic regional CGE model, we simulate and explore more features of each Chinese province’s MAC curve. The shapes of the MAC curve at the regional level also help us study the choice of carbon abatement policies based on the combination of this mechanism and Weitzman’s rule.

Firstly, we find that regional MAC curves shift upward over time, which means that the increase in abatement cost and the difference among MAC curves also become larger after year 2015 because the emission intensity targets grow tighter in all regions. This result is consistent with our common sense.

Secondly, kink points occur on all regional MAC curves, and these kink points have very different characteristics. When facing an emission constraint, each region must adjust its optimal production behaviour by balancing the cost of abatement activity input and the cost of reducing output. The existence of intensity targets causes the initial abatement activity cost to be higher than the cost of reducing output. These high costs cause inconsistent behaviour in reducing emissions and lead to the occurrence of kink points in MAC curves. Moreover, each region’s emission intensity targets and cost share of inputs also affect the differences in kink points.

Thirdly, the choice of price policies or quantity policies is highly dependent on the shape of the MB curve. Simulation results show that the positions of the kinked points of the regional MAC curves shift rightward over time, resulting in the actual reduction rate located to the left of the kink points. The slope of the MAC curve to the left of the kink point is higher than that on the right, indicating a higher possibility of suffering greater efficiency losses from adopting price control policies than from adopting quantity policies. A sensitivity analysis of the slope of the MB curve suggests that quantity instruments are only suitable when the MB curve is steeper than a certain level.

Fourthly, the results are especially instructive for China as it is trying to build its national emission trading scheme while it has also announced its long-term emission intensity target. Our simulation results show that there are large possibilities that most regions will suffer “lock-in effect” after year 2015 if emission cap of national ETS remains stable or decline slowly (which means emission reduction rate is small). Sectors will only reduce output levels under “lock-in effect”, thus no technology progress or structure change will occur. To avoid this, policy makers should consider carefully about whether to apply both low-carbon policies to all sectors or not. Moreover, if both policies are used in practical, we can get two important implications from our results. First, settings of caps in different regions are important because levels of caps determine whether intensity targets take effect or not. If intensity targets take effect, there will occur distortions in sectors’ optimal behavior. Second, more policies such as encouraging development of low-carbon technologies should be introduced to change positions of kink points to avoid “lock-in effect”.

Finally, our model can be extended to evaluate more hot debates related to carbon policies in further studies. First, bottom-up models can be introduced to depict low-carbon technologies and policy induced “lock-in” effect can thus be studied in more detail. Second, our conclusion can contribute to studying optimal sector coverage problems for those countries which are building their own emission trading schemes to avoid “lock-in effect”.

VIII. Appendix

In this section, we will perform some robustness analyses on the MAC curve. As we have already discussed, the choice of policy instrument is primarily determined by the kink points of MAC curves. The occurrence of kink points is determined by three factors: emission intensity target, cost share of inputs and elasticity of substitution among inputs. Uncertainties about all three factors may affect the equilibrium result in the CGE model. The uncertainties of the first two factors are related to model setting and parameter calibration, and their effect is relatively small because both BAU scenario settings and cost share are drawn from existing policy and real data. Therefore, the only uncertainty we should be concerned about is choosing free parameters such as the elasticity of substitution (Mansur and Whalley, 1984).

Generally, most free parameters in the CGE model are chosen from empirical studies, at both the regional and industry level. However, these estimation results are highly dependent on the specific regression models and data used by researchers. Thus, the elasticity of substitution values used in the CGE model may vary across a wide range, which may cause very different equilibrium results. In this section, we will conduct robustness analyses of the elasticity of substitution among the different energies that play the most important role in this paper.

In the CGE model, the elasticity of substitution used in the CES function ranges from zero to infinity. However, in most research studies, this range is zero to six, and most functions take this value as one, such as the Cobb-Douglas function. For this reason, it is reasonable to assume that the elasticity of substitution has an upper bound greater than zero.

Several methods have been proposed to test the uncertainty of free parameters in the CGE model (Wigle, 1991; Harrison et al., 1993). These methods can be divided into five categories: limited sensitivity analysis, conditional systematic sensitivity analysis, unconditional systematic sensitivity analysis, Bayes' method and the extremum method. Here, we adopt the limited sensitivity analysis method, which includes the elasticity of substitution among energy inputs.

The elasticity of substitution among energies adopted in this paper is 0.5. We suppose the elasticity bears beta distribution $\sigma \sim Be(a,b)$ to better represent the boundary feature (Wang & Chen, 2006). The expectation value is 0.5 and the standard deviation is 0.3. The upper bound and lower bound are 0 and 2, respectively. From these conditions, we can calculate the value of two parameters:

$$f(x)=\frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}\left(\frac{x}{2}\right)^{a-1}\left(1-\frac{x}{2}\right)^{\beta-1},0<x<2 \tag{16}$$

$$\frac{a}{a+b}=0.5,\frac{ab}{(a+b)^2(a+b+1)}=0.3^2 \tag{17}$$

From equation (17), we obtain *a* equals 11/6 and *b* equals 33/6. In our Monte Carlo simulation, we assume a 10% emission reduction rate in year 2010 in Beijing to be representative due to the complexity of the entire CGE model. In the simulation, we draw the elasticity of substitution from the beta distribution 1000 times and solve the equilibrium results each time to obtain the distribution of marginal abatement cost.

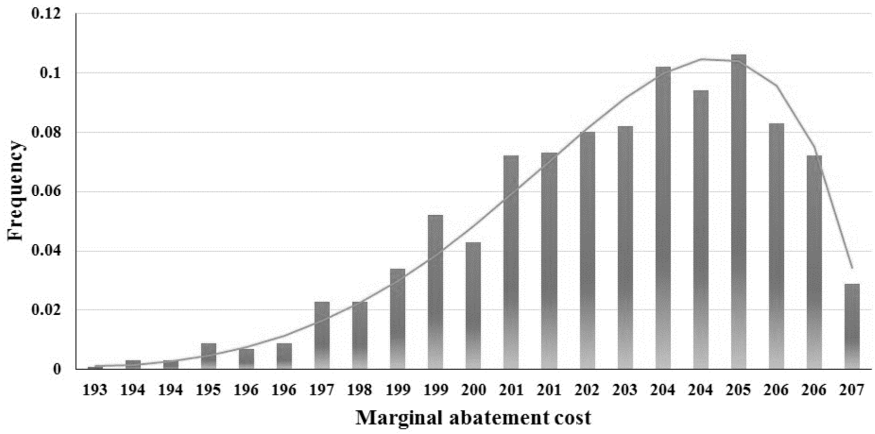

Figure 7 Distribution of marginal abatement cost in Beijing in 2010 under a 10% emission reduction

In Figure 7, the histogram is the simulation result and the solid line is the linear transformation of the standard beta distribution. The scale coefficients of linear transformation come from regression analyses of the simulation results and the elasticity of substitution drawn from beta distribution shown in Table 3.

Table 3 Result of regression analysis of the marginal abatement cost

Regression equation: MAC = C + beta * sigma + ε		
	Constant	Slope
Estimation Value	206.791***	-9.074***
Standard Deviation	（0.00849）	（0.01444）

*** implies it is significant at a 1% level.

Table 4 Summary statistics of Monte Carlo result

Index	Real Value	Sample value	Fitted value
Average	202.14	202.29	202.25
Standard Deviation	N/A	2.86	2.72
Coefficient of Variation	N/A	0.014	0.013

Table 4 gives three values for the marginal abatement cost. The real value comes from the original CGE model, which has no standard deviation. The sample value is the average value of 1000 simulations. The fitted value is the expected value of the linear transformed beta distribution. We can see that all values are very close to each other, which indicates that the sample mean value converges to the real value. The confidence interval of the marginal abatement cost under the 95% significance level is [196.03,206.21]. As a percentage, this confidence interval is [-3.0%, 2.0%], which is an acceptable range. Table 4 gives the corresponding confidence intervals for marginal abatement costs under different emission reduction target rates:

Table 5 Corresponding errors of different carbon abatement costs

<table>
<tr><th rowspan="2">Percentage</th><th colspan="2">Confidence Interval（95%）</th><th colspan="2">Confidence interval of percentage</th></tr>
<tr><th>Lower Bound</th><th>Lower Bound</th><th>Lower Bound</th><th>Lower Bound</th></tr>
<tr><td>2%</td><td>63.06</td><td>75.62</td><td>-7.6%</td><td>10.8%</td></tr>
<tr><td>4%</td><td>129.40</td><td>132.50</td><td>-0.9%</td><td>1.4%</td></tr>
<tr><td>6%</td><td>164.45</td><td>172.80</td><td>-2.9%</td><td>2.0%</td></tr>
<tr><td>8%</td><td>179.94</td><td>189.14</td><td>-3.0%</td><td>2.0%</td></tr>
<tr><td>10%</td><td>196.12</td><td>206.19</td><td>-3.0%</td><td>2.0%</td></tr>
</table>

The results in Table 5 imply that the confidence interval converges rapidly to a stable range. In Beijing's case, the actual emission reduction rate in 2010 is 9.5%, which means that the confidence interval of its marginal abatement cost is stable enough to make a policy choice. This result shows that the simulation results in our CGE model are robust and reliable.

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